Observation of Strong Variability in the X-Ray Emission from Markarian 421 Correlated with the May 1996 TeV Flare

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Abstract. We observed the BL Lac object Markarian 421 with the X-ray satellite RXTE and the Whipple Air Cerenkov Telescope during a two week correlated X-ray/gamma-ray campaign in May 1996. Two dramatic outbursts with extremely rapid and strong flux variations were observed at TeV energies during this period. The X-ray emission in the 2-10 keV band was highly variable and reached a peak flux of 5.6×10^{-10} erg cm^{-2} s^{-1}, a historic high. Similar behavior was observed for the TeV emission. In contrast to earlier near-simultaneous X-ray/gamma-ray observations of Mrk 421, the variability amplitude is much larger at TeV than at X-ray energies. This behavior is expected in Synchrotron Self-Compton models.

INTRODUCTION

Present blazar research focuses on the question of how relativistic jets are formed and how particles are accelerated to energies beyond a TeV. To find an answer to this question we are trying to understand the very basic properties of the jet, i.e. particle population, velocities, total energy, and magnetic field strength. The non-thermal blazar emission from radio to UV is generally thought to be synchrotron radiation beamed from a relativistic jet viewed at small angles. In the case of Markarian 421, the synchrotron emission dominates up to X-ray energies. A second component, observed above the synchrotron break, is typically relatively flat and extends to X-ray and sometimes to gamma-ray energies, as in the case for Markarian 421.

In the context of current theoretical models invoked to explain the broadband energy spectrum of Markarian 421 and other similar X-ray selected BL Lac objects, correlated observations can be used to understand the physics of the electron population believed to be the progenitor of the high energy emission. The energy spectrum near the spectral break around a few keV may give a handle on the maximum electron energy in the system. Mufson et al. (1990) report a two-component

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X-ray spectrum with a steepening tail above 4.5 keV. This suggests the contribution of two different components to the X-ray emission: synchrotron radiation from the highest energy electrons and inverse-Compton scattered photons from the lowest energy electrons. In such a scenario, the X-ray band plays a crucial role in the study of the broadband emission [12].

Markarian 421 has been monitored previously and has shown rapid variability on short time scales. Detailed studies based on EXOSAT observations showed significant variation in the 0.5-10 keV band on time scales from several hours to several days [5]. This strongly suggests that typical X-ray high states are relatively short lived. Near coincident flaring in the X-ray and TeV gamma-ray emission was observed in 1994 and in 1995 [1,6] which prompted us to propose extensive observations with the newly launched X-ray satellite, XTE, and the Whipple telescope.

OBSERVATIONS

The X-ray observations discussed here were carried out with the PCA (Proportional Counter Array) onboard the Rossi X-Ray Timing Explorer [2]. Between 1996 May 4 and May 21, the PCA was pointed on average 4 times every day at Markarian 421. A typical observation resulted in a net exposure of 600 seconds.

The individual X-ray spectra were fitted with a single power-law model with energy spectral index α, $F(E) = F_0 E^{-\alpha}$, with the absorbing column N_H fixed at the Galactic value ($1.5 \times 10^{20} cm^{-2}$) [3]. We found that the simple power law function describes the data well in the energy range between 2 and 10 keV if we allow for a 2% systematic error for energies between 3.5 and 6 keV. This additional systematic error accounts for small uncertainties in the channel-to-energy conversion which was not finalized at the time of this analysis. Alternately, we also have applied a single power-law model and allowed for a varying column density. While this resulted in slightly improved χ^2 values for fits between 2 keV and 10 keV, it also resulted in N_H values ≈ 20 times larger than the Galactic value. A broken power-law model, successfully applied to ASCA data [10], did not fit any of the spectra well.

RESULTS

During the observation period two very remarkable outbursts were observed at TeV energies (May 7 and May 15). The May 7 flare is the most intense flare recorded at TeV energies [4]. During the course of 2 hours of observing, the gamma-ray emission increased steadily from 4 times to about 30 times the average flux. The second TeV flare (May 15) was less pronounced but shows an even shorter doubling time of ≈ 20 minutes.

The time history of the May 1996 X-ray and TeV observations is shown in figure 1. The X-ray light curve during the high state between day 125 and day 129 shows very rapid quasi-periodic variations with similar rise and fall times of the order of several hours. This behavior is an indication that geometrical effects may need to

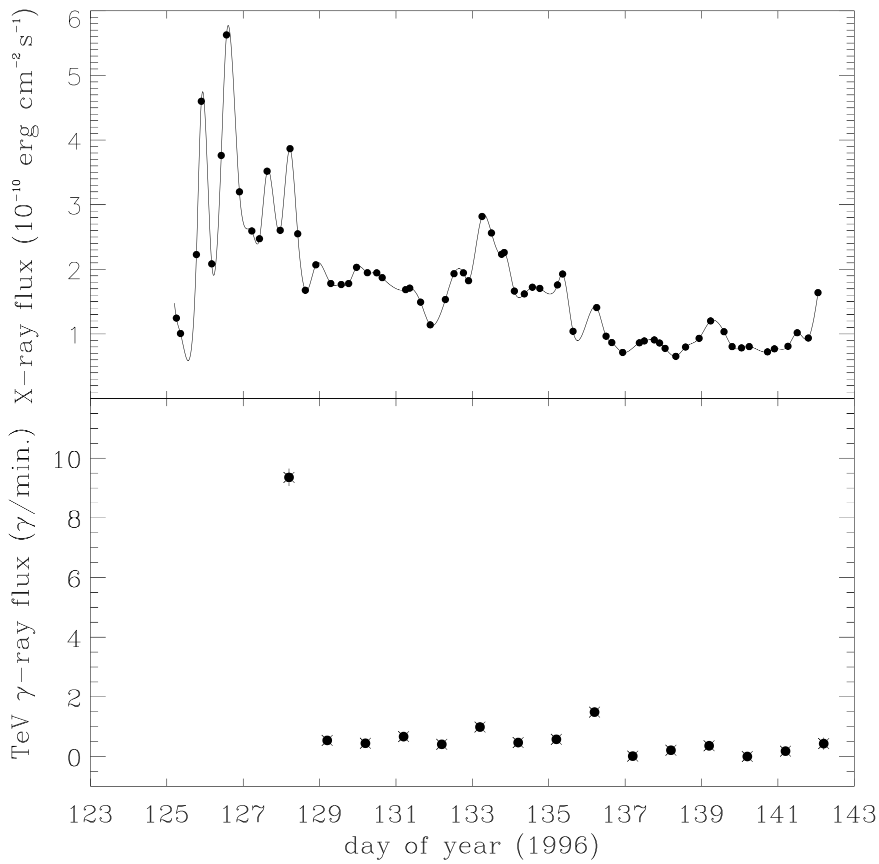

FIGURE 1. The X-ray (2-10 keV) and TeV (> 300 GeV) emission from Markarian 421 during May 1996. We included a fitted cubic spline function as a guidance for the eye.

be considered in order to explain the observed variability. The 2-10 keV flux was high throughout the observing period compared to previous measurements (see [9] for a compilation of the long term variability of Markarian 421). On May 5 (day 126) the 2-10 keV flux increased to 5.6×10^{-10} $erg\ cm^{-2}s^{-1}$, brighter than all previous observations.

The TeV high state on May 7 (day 128) clearly occurred during strong activity in the X-ray band. Restricted by the bright moon, TeV observations could not be obtained prior to day 128. This leaves some ambiguity in determining the exact time delay between TeV and X-ray high state. However, the close coincidence of the TeV and X-ray flare suggests that both arise from the same electron population in the jet.

An interesting conclusion can be drawn from comparing the relative amplitudes of the flare states in both bands. While previous flare observations [1,6] claim a comparable amplitude in the variability, during this observation, the flux at TeV energies rose a factor of ≈ 30 above the quiescent level, compared to a factor of ≈ 5 for the keV flux. This is expected in Synchrotron Self-Compton (SSC)

models where the X-rays are the seed photons that are Comptonized to produce the TeV flux. Simultaneous optical data taken with the 48 inch optical telescope on Mt. Hopkins did not show an increase in the flux during this period [7]. This also confirms previous observations where the flux at longer wavelengths remained relatively constant during strong X-ray/TeV flares.

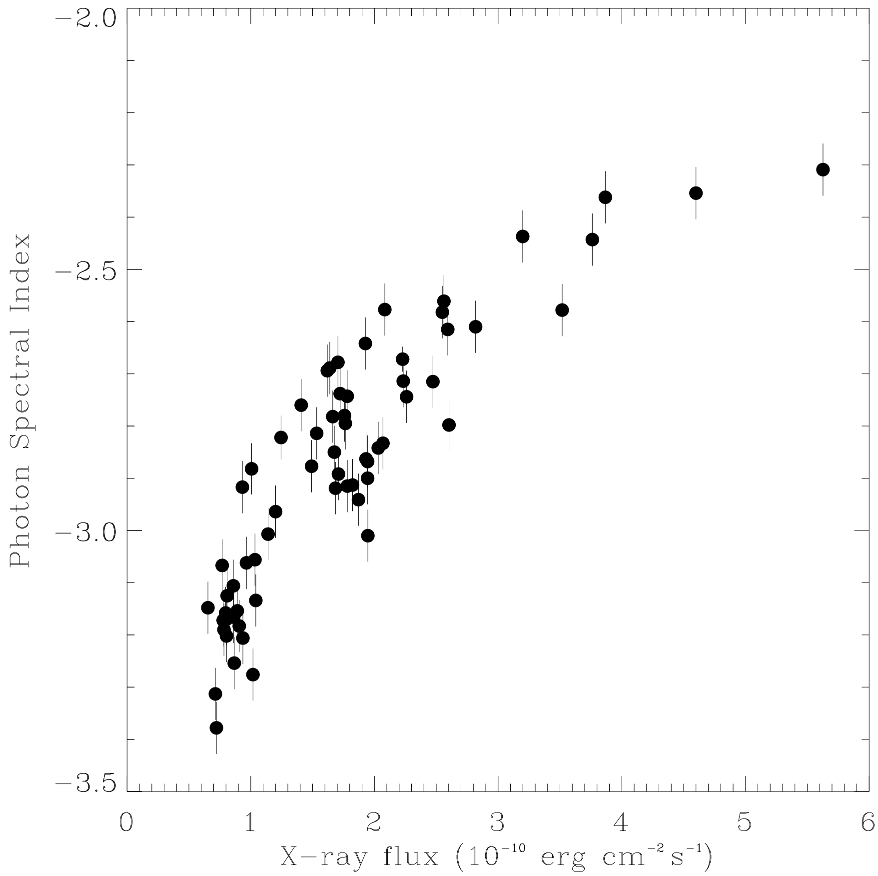

FIGURE 2. Correlation between the observed 2-10 keV flux and the photon spectral index α (A single power-law function with index α, such that the flux $\Phi(\mathrm{E}) = \Phi_0 \mathrm{E}^{-\alpha}$, describes the spectra well).

The variation in the observed flux shows a strong correlation with the photon spectral index (figure 2). A spectral hardening is observed during a phase of increased emission. This can be explained by the injection of an electron component more rapid than typical synchrotron cooling time scales [11].

SUMMARY

We detected strong variability in the 2-10 keV emission from Markarian 421 during observations carried out in May 1996, parallel to the TeV observations by

the Whipple Collaboration. The correlated variability of X-ray and TeV emission strongly supports models which involve synchrotron radiation and the Inverse Compton (IC) process to describe the spectral energy distributions of blazars. In the case where the seed photons for the IC process are the synchrotron photons (SSC models), the IC flare amplitude is expected to be proportional to the square of the synchrotron flare amplitude. The presented data suggest this scenario, in which, at least in the case of Markarian 421, the variability in the TeV luminosity (IC) is caused by variability of the X-ray photons (synchrotron). The quasi-periodicity in the X-ray emission, with similar time scales in the rise and fall times of the individual flares indicate that geometric effects may have to be considered to understand the perturbations which lead to the observed variability.

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